Incorporating Fishermen's Local Knowledge and Behavior into Geographical Information Systems (GIS) for Designing Marine Protected Areas in Oceania

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Drawing on our experience in establishing marine protected areas (MPAs) in the Roviana and Vonavona Lagoons, New Georgia, Solomon Islands, this paper shows how a geographical information system (GIS) database can be used to incorporate socio-spatial information, such as indigenous knowledge and artisanal fishing data, along with biophysical and other information to assist in MPA design. We argue that converting peoples' knowledge and socioecological behavior into geo-spatial data allows researchers to formulate hypotheses regarding human responses to inter- and intra-habitat variability, along with other marine ecological processes, and help in the designing and implementation of resource management strategies in a cost-effective and participatory way, bridging the gap between indigenous and Western cognitions of seascapes. More generally, we show the significance of combining spatial tools, anthropological fieldwork, and social and natural science methods for studying artisanal fisheries with the goal of aiding the design of marine protected areas.

Key words: Geographical Information Systems (GIS), indigenous ecological knowledge, fishing, community-based marine protected areas (CBMPAs), Solomon Islands, Oceania

Introduction

Environmental social scientists are increasingly realizing the importance of geographical information systems (GIS) and remote sensing (RS) techniques (often referred to collectively as *geomatics*) in studying diverse spatio-temporal dimensions of human-environmental relationships

(Aldenderfer and Maschner 1996; Conant 1994; Nyerges and Green 2000) and in employing such knowledge to design and implement resource management strategies (Bowman et al. 2004). Spatio-temporal, multi-dimensional GIS, and remote sensing data can serve to verify, expand, or reveal site-specific or regional patterns of human demographic, political, economic, socio-cultural, and ecological dynamics that may not be obvious to researchers on the ground. The use of GIS and RS techniques in tandem with social and natural science research promises to deepen our understanding of important anthropological questions. Examples include: (1) how spatial patterns of grazing pressures across agro-pastoral landscapes are determined by different socio-political and economic processes (Turner 2003); (2) how demographic and social class differentiation shifts may influence deforestation patterns (Moran et al. 1994; Sussman et al. 1994); (3) how diverse ethnic groups culturally construct the spatio-temporal characteristics of their landscapes (Jiang 2003; Mark and Turk 2003; Robbins 2003); (4) how indigenous land and sea tenure systems are spatially distributed in particular regions and how they change across time (Mohamed and Ventura 2000); and (5) how the spatio-temporal mapping of indigenous ecological knowledge can foster biodiversity conservation (Rundstrom 1995; Balram et al. 2004).

The use of GIS for mapping marine resources for management and conservation is a growing field of interest

Figure 1. The Solomon Islands
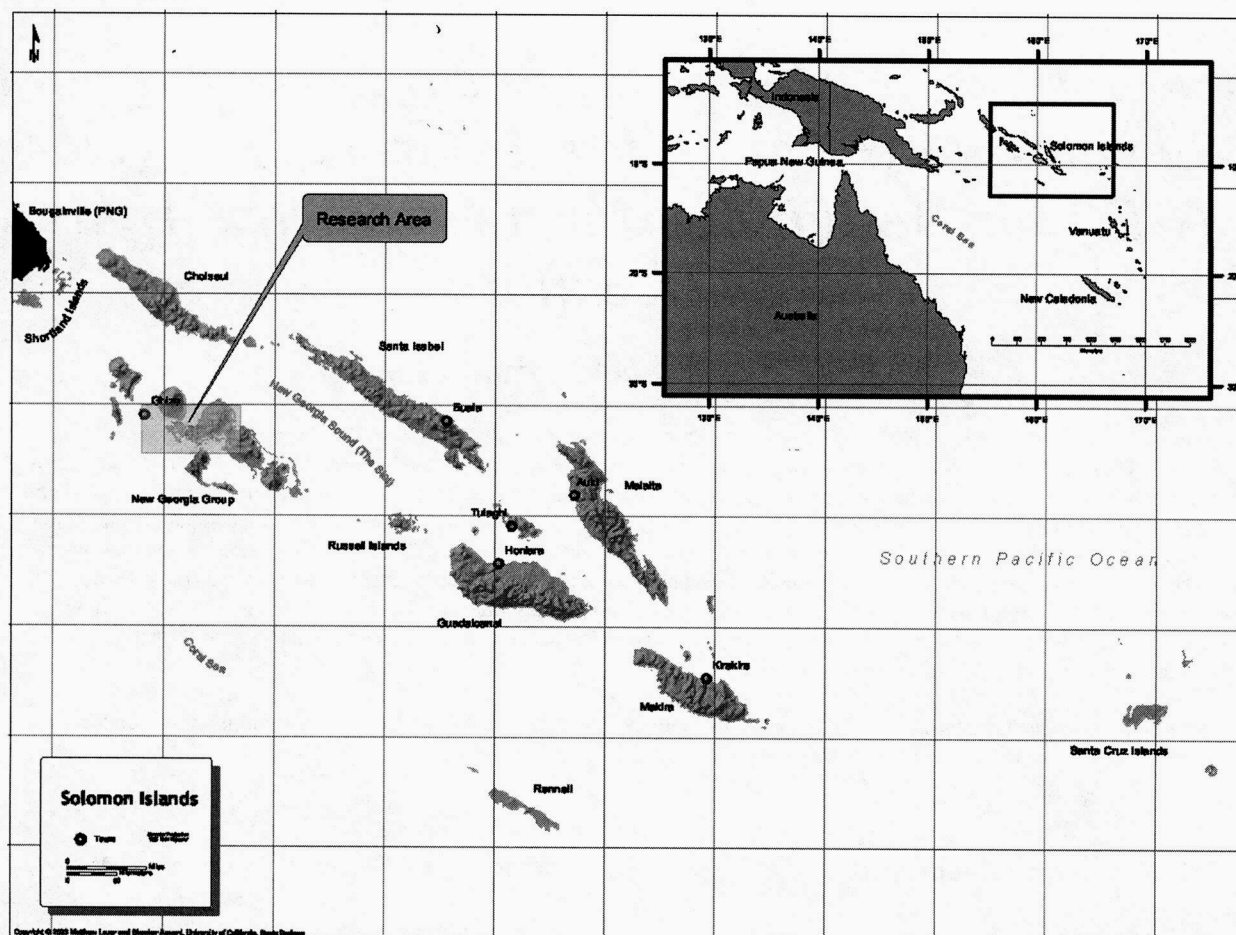
(e.g., Bates and James 2002; Mumby et al. 1995; Turner and Klaus 2005; Villa et al. 2002), although local expert ecological knowledge is rarely incorporated into a GIS for marine resource management purposes. In the context of artisanal fisheries management, geomatics coupled with ethnographic and marine science research proved useful in delineating and cataloguing reefs belonging to the Miskito Indians in coastal Nicaragua (Nietschmann 1995), for mapping fishing spots in southeastern Brazil and helping local fishermen use this knowledge to defend their territories from industrial trawlers (Begossi 2001), for systematizing indigenous ecological knowledge into geo-spatial data to guide fishery management in Bang Saphan Bay, Thailand (Anuchiracheeva et al. 2003), and for mapping indigenous knowledge regarding bumphead parrotfish nursery, schooling, burrowing, and capture areas in the Roviana Lagoon, Solomon Islands, and for using this geo-spatial data for scientific research and the designing of marine protected areas (Aswani and Hamilton 2004a).

These examples demonstrate the power of geomatics in representing visually site-specific spatio-temporal patterns

of human and ecological dynamics. Further, using local knowledge and activities to build a GIS (Balram et al. 2004; Stouffle et al. 1994) and management plan (Johannes 1998; Roberts 2000) is a cost-effective strategy for obtaining missing data essential for selecting biodiversity conservation priority areas, data which would otherwise take years to collect. In addition, participatory GIS has the double benefit of empowering indigenous peoples to map their land and sea territories while furnishing a research context for them to contribute important insights about their environment.

In this paper, we show how a GIS database can be used to incorporate socio-spatial information, such as indigenous ecological knowledge and artisanal fishing data, along with biophysical and other information to assist in the design of marine protected areas (MPAs). The techniques employed for integrating cognitive and behavioral information into a GIS through the use of local informants are delineated. We argue that converting peoples' knowledge and socioecological behavior into geo-spatial representations allows researchers to: (1) distinctively conceptualize human foraging strategies spatio-temporally; (2) illustrate how human cognitive maps of the

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Figure 2. The Roviana and Vonavona Lagoons, Western Solomon Islands

seascape and marine organisms translate into actual resource classification, use, and allocation geographically (sea tenure); (3) recognize local ecological processes, including habitat structure (habitat delineation), species composition and distribution, and spatio-temporal biological events (spawning aggregations) spatially; and (4) plausibly identify sites that incorporate the ecological processes that support biodiversity, including the presence of exploitable species, vulnerable life stages, and inter-connectivity among habitats.

This socio-spatial knowledge is significant for two reasons. First, it can assist in formulating hypotheses regarding human responses to inter- and intra-habitat variability, along with other marine ecological processes; second, it can help in the design and implementation of resource management strategies in a cost-effective and participatory way. We draw from our research experience with GIS and our experience in establishing marine protected areas in the Roviana and Vonavona Lagoons, New Georgia, Solomon Islands (Figs. 1 and 2) to provide a hands-on example to illustrate our case.

We demonstrate the significance of combining spatial tools, anthropological fieldwork, and social and natural science methods for studying artisanal fisheries with the goal of aiding the design of marine protected areas. We also illustrate a "public participation GIS," in which local concerns, interests, and knowledge are included in planning a GIS (Poole 1995; cf. Rundstrom 1995; Robbins 2003). Finally, we propose that public participation in GIS can assist in bridging the gap between indigenous and Western cognitions of landscapes and seascapes (Herlihy and Knapp 2003) and enhance local participation in community-based fisheries management. This approach can be applied in tandem with more conventional marine science methods for designing and establishing marine protected areas in the Pacific Islands.

Study Site

The Roviana and Vonavona Lagoons are in the Western Solomon Islands of the South Pacific (Fig. 2). The lagoons

Figure 3. Roviana and Vonavona Marine Protected Area (MPA) Network
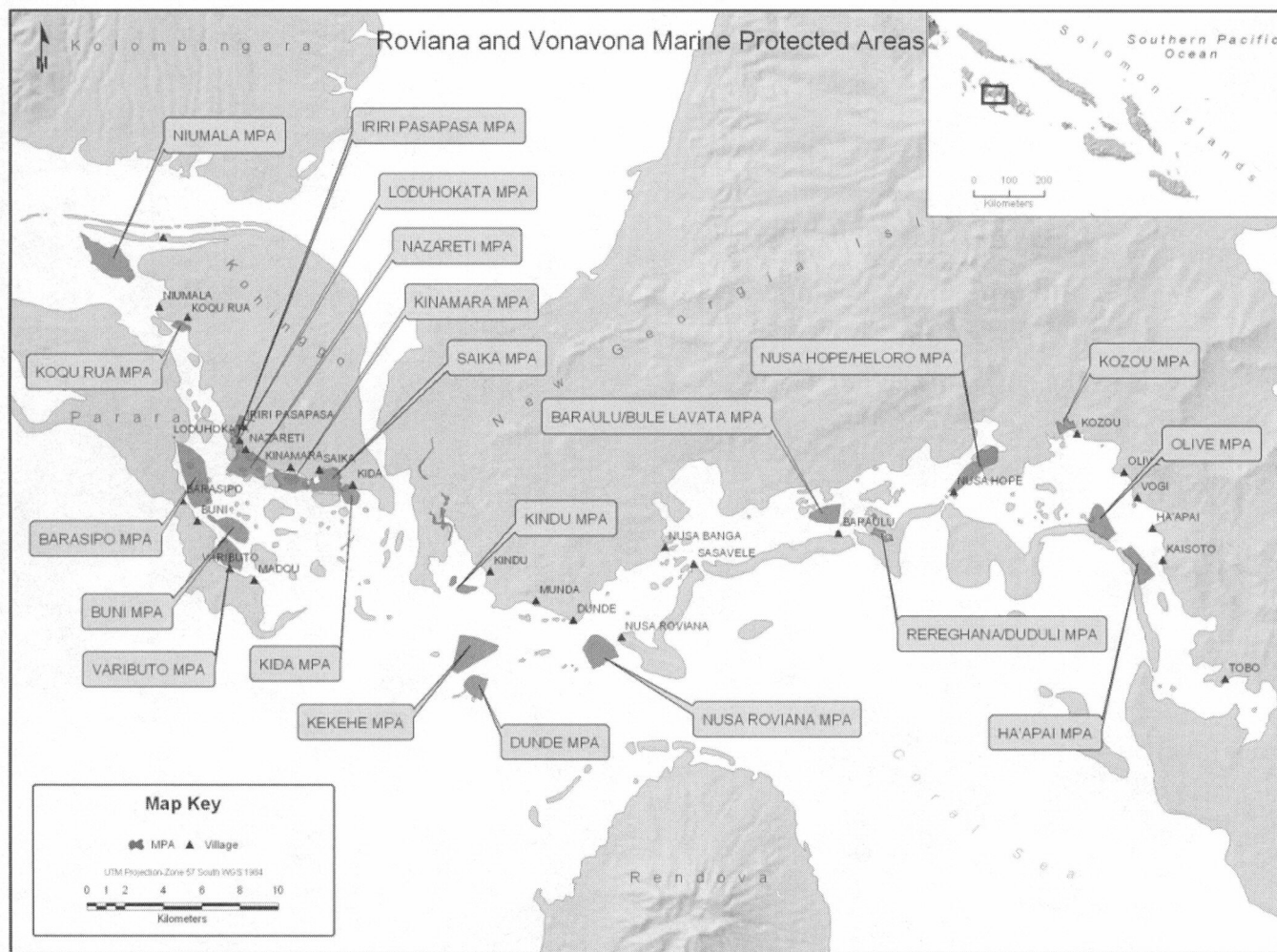
Designed by Matthew Lauer, University of California, Santa Barbara.

are formed of raised offshore coral islands that developed during the Pleistocene period due to sea-level changes and the accumulation of coral limestone, organic debris, and volcanic detritus (Stanton and Bell 1969). The outer lagoon shorelines are composed of rugged, notched limestone with many inlets, bays, carbonate sand beaches, and moats (Stoddart 1969), and the inner lagoons house small islets, coral reefs, and intertidal reef flats. Various marine habitats, including grass beds, mangroves, freshwater swamps, river estuaries, sand channels, shallow coral reefs, and outer reef drops dot the lagoons. The Roviana and Vonavona lagoons lie within the Bismarck-Solomon Seas eco-region, which is a large marine ecosystem that extends through the Solomon Islands, the north coast of Papua New Guinea, and the northern West Papua region. Regional marine biotopes are highly diverse, productive, and moderately undamaged by human activities, making this area one of the world's marine biodiversity hotspots (WWF South Sea Program 2003). More than twelve thousand people inhabit the Roviana and

Vonavona area, and the region's population growth rate is high (National Census 1999). Local community leaders exercise governance and management over use of and access to natural resources within their respective customary land and sea estates. However, community-based management has not guaranteed the sustainable use of natural resources, as a population explosion and rampant developmental pressures (logging and industrial fisheries) are increasingly threatening the ecology and social stability of this region.

Responding to these threats, we established a marine conservation project in 1999 (Aswani et al. 2004). Our aim was to create a network of MPAs and to launch infrastructural development projects to assist rural communities. The biological objectives of the current MPA network are to protect vulnerable species and habitats (i.e., biodiversity and ecosystem function), to protect susceptible life history stages (i.e., spawning and nursery grounds), and to enhance fisheries productivity in the region. The social objectives are to build upon practices with which the community members are familiar

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(e.g., customary sea tenure and indigenous ecological knowledge) and to enhance community well-being throughout the region. Local people are better able to grasp the biological and social value of the MPA network and to understand the use restrictions it requires (Aswani and Hamilton 2004b) when the interdependence of conservation and the health and welfare of local communities is made explicit. Currently, 21 MPAs have been established, most of which have been set up as permanent "no-take" zones (Fig. 3). In addition, a number of small infrastructure improvements have been initiated (e.g., clinics, schools, and community halls) across the region (Aswani and Weiant 2004).[1]

A number of MPA locations were chosen for their ecological and social significance through a combination of locally driven assessments (e.g., proximity to the village for monitoring and enforcement) and by the information gained from our research. Note that MPAs were the best management prescription considering the sociopolitical context of the region. Policing restrictions on catch and size is difficult given the extent of the lagoon area, but spotting poachers entering and exiting the closures is not as difficult. We coupled indigenous ecological knowledge (GIS mapping of locally identified habitats and biological events) with marine science (underwater visual census [UVC] surveys to study aspects of life history characteristics of target species) to identify vulnerable habitats and critical life stages of susceptible species across various areas of the lagoon (Aswani and Hamilton 2004a). We also incorporated longitudinal data (1994-2004) on human fishing activities (Aswani 1998a) into the GIS to examine spatial and temporal patterns of human fishing effort and yields. Finally, we systematically studied customary sea tenure (CST) across the region in order to select sites in which there was minimal public contest over natural resources and sea boundaries (see Aswani 1999, 2002, 2005).

Methods

Fishermen's Knowledge and GIS

Data on indigenous ecological knowledge was documented through direct participation in fishing forays and through interviews with fishermen. Open-ended and structured interviews were conducted for a period of 12 years (1992-2004) with more than 300 young (18-39), middle-aged (40-59), and elderly (60 >) men and women from across villages in the lagoons. While we sought to interview active and experienced fishermen via a snowball sample, the general population was also questioned through a random stratified sample. To better conceptualize the seascape, informants were asked a range of questions pertaining to the spatio-temporal characteristics of their fishing grounds and existing benthic habitats, as well as other associated biological processes. Fishers identified around fourteen major habitat types and six minor ones, as well as 615 locally delineated areas throughout the region. The latter were mapped onto aerial photographs of the Roviana and Vonavona Lagoons manually (Aswani 1997),

thus establishing the spatial foundation for the ensuing GIS visual representation.

Next, we incorporated indigenous marine ecological knowledge into a GIS database by delineating the boundaries of locally identified biophysical areas with Geographical Positioning System (GPS) instruments and recorded the associated habitats and biological organisms. To aid our efforts in collecting the eco-spatial indigenous knowledge, we first generated a base map with aerial photography. This involved, first, digitizing a set of 9-inch by 9-inch black-and-white aerial photographs (91 photographs) of the Roviana and Vonavona lagoons (taken in 1984 by the Solomon Islands Government with a scale of 1:24,000) and, second, collecting ground control points so that the images could be geo-rectified and positioned accurately in spatial coordinates.[2] The digitized base map of aerial photos was loaded onto a portable computer and served as an important cartographic tool for the researchers and local informants when collecting spatial data in the region.

Once the base map of digitized aerial photos was completed, we worked with local fishers to map the seascape with GPS receivers — a participatory aspect of our work through which local people interacted with and generated data for the GIS. We focused primarily on indigenously defined biophysical areas, fishing grounds and spots, and associated marine habitats, including, among others, inner-lagoon reefs (sagauru masa) and outer-lagoon reef drops (teqoteqo pa vuragare) (Fig. 4). In addition, we recorded the locations of spawning, nursery, burrowing, and aggregating sites for particular species within each recognized area. Local fishermen from each community guided a researcher in a small boat around the perimeter of each named area, which could, or might not, correspond with the boundaries of particular marine biotopes (e.g., seagrass beds). Singular biological characteristics (e.g., aggregation sites) were located if they were found within the site and pinpointed with the GPS. Knowledgeable informants were selected to help map these characteristics of the seascape by means of a snowball sample and through meetings with local elders. In addition, as detailed in Aswani and Lauer (n.d.), informants demarcated the boundaries of the underlying abiotic and biotic substrates using a felt tip marker directly on large format printouts of aerial photographs. The resulting paper maps, with the respective benthic types drawn on them, were scanned, and the image files were loaded into the GIS for geo-rectification. Thereafter, we employed conventional quadrat field-dive surveys for ground-truthing the accuracy of local habitat identification.

Over a period of four field seasons (totaling over 7 months), we mapped 491 indigenously defined and named sites and their major biological characteristics across Roviana and Vonavona, which included the lagoon habitat types targeted for conservation. The spatial extent of the area (represented as either lines or polygons) and the location of particular biological characteristics (represented usually as points) collected with the GPS receivers were consolidated into a large file and imported into our GIS database as a layer (sometimes called a theme or coverage). In Figure 4, this data set is displayed as

Figure 4. Indigenously Delineated Biophysical Areas of Rovinana and Vonavona Lagoons, Particularly Those Associated with Inner-lagoon Reefs and Outer-lagoon Reef Drops
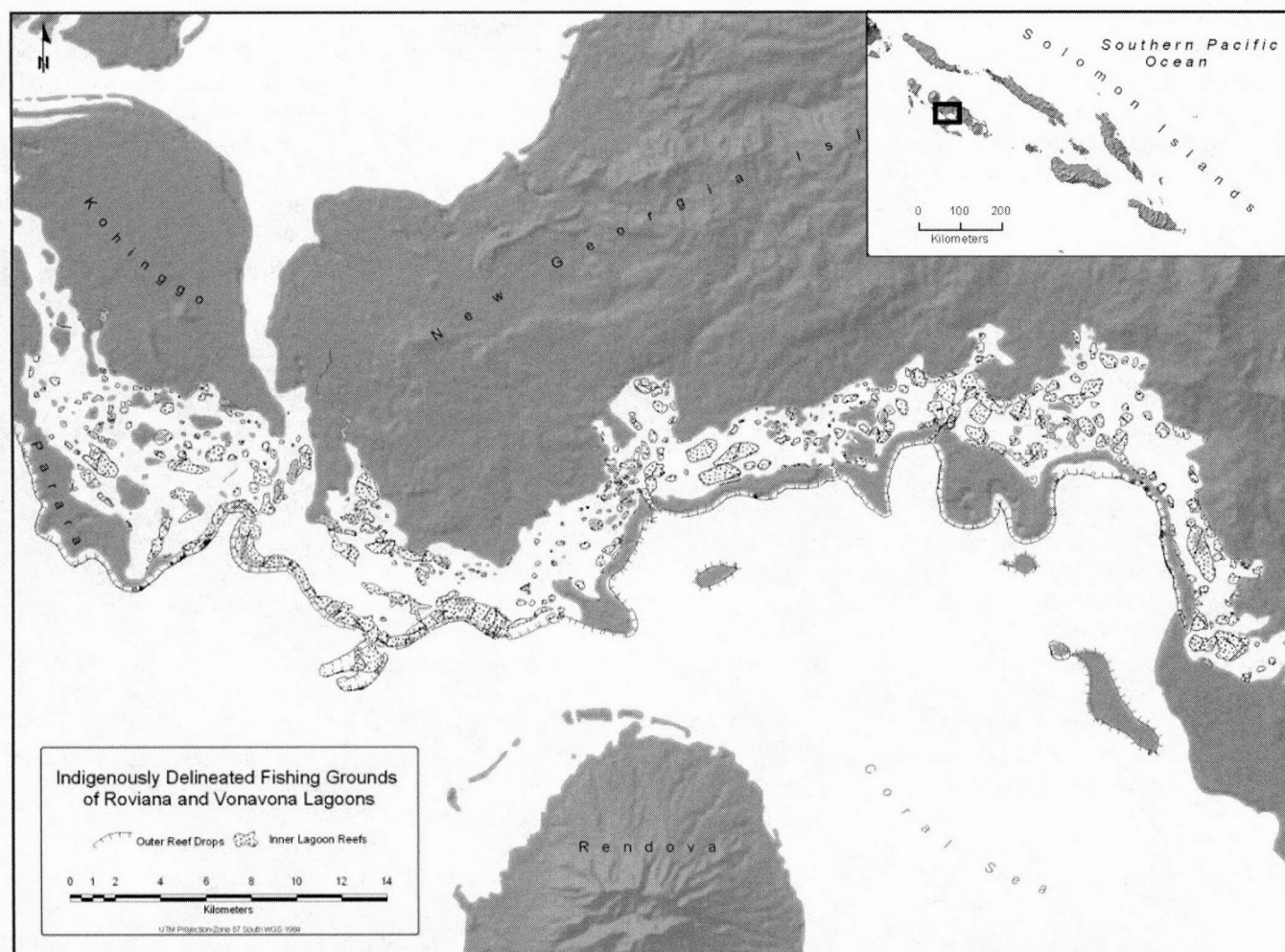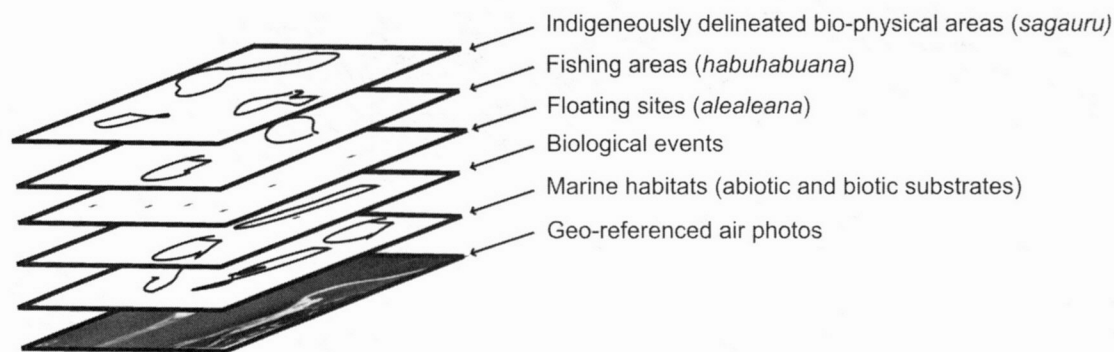

an overlay on top of a topographic map to produce a display of the entire lagoon reef system as defined by the local people. Visualizing the patchwork of locally defined sites and associated habitats (Franklin et al. 2002) allowed us to select sites for potential sampling when conducting conventional marine ecological surveys (e.g., Aswani et al. 2004). It also provided clues about the Roviana people's conceptualization of the seascape and the inter-connectivity of different habitats used by humans. To sharpen our focus, we provide examples of this work for the Baraulu and Nusa Hope Village MPAs.

Fishermen's Behavior and GIS

Spatial and temporal characteristics of fishing behavior were displayed for Baraulu and Nusa Hope villages by querying our GIS database and then displaying the data derived from the queries. To do this, we linked foraging data that we had collected over the past 12 years with our GPS data set

of indigenously defined areas. The foraging data subset was employed earlier to test several optimal foraging theory hypotheses (Aswani 1998a). Human ecologists have routinely employed foraging models to predict various aspects of human foraging behavior (Bird and Bird 1997; Smith 1991) but have rarely coupled the power of GIS with their analyses (but see Schweik 2000). For this study, we tested a hypothesis drawn from the patch choice model (MacArthur and Pianka 1966) to provide understanding of fishermen's patch choices across spatio-temporal variation and, most importantly, to visually display foraging patterns across diverse marine habitats and during different seasons of the year. The patch choice model predicts foragers will select patches (e.g., habitats and/or fishing grounds) according to the mean rate of return for that patch. Resource patches are ranked from highest- to lowest-yielding and are added to the foraging range until savings in travel time are outweighed by a lowering in the mean rate of return for the set of utilized patches (Winterhalder 1981). Using this model,

HUMAN ORGANIZATION

Indigeneously delineated bio-physical areas (*sagauru*)

Fishing areas (*habuhabuana*)

Floating sites (*alealeana*)

Biological events

Marine habitats (abiotic and biotic substrates)

Geo-referenced air photos

we tested the hypothesis that overall time allocation to a habitat type (set of patches) increases when seasonal productivity for that habitat increases and is higher than that of other habitats. Conversely, overall time allocation to a habitat type decreases when seasonal productivity for that set of patches declines and is lower than that of other habitats.

We do not discuss a number of theoretical and methodological issues concerning the application of foraging models in marine contexts, and we recognize that our application is rudimentary given current advances in human behavioral ecology (Winterhalder and Smith 2000). Our aim, however, is not to test foraging models *per se* but rather to show how the spatial-temporal characteristics of site-specific foraging patterns can be revealed by querying and displaying the information with GIS. We tested the foraging hypothesis by analyzing 1,946 hours of fishing data for Baraulu and 526 hours for Nusa Hope. Note that the original Baraulu and Nusa Hope data sets encompassed 2,893 and 755 hours of foraging data, respectively. The data subset analyzed is smaller because only patch names that appeared in both the original foraging subsets (1994-95) and in the more recently collected GPS database of mapped, named areas (2001-2004) could be analyzed. In addition, only fishing events for hand-lining (trolling, bottom-lining, angling, etc.) were included. To use relative abundance measurements to determine local yields, we sorted the data according to the type of fishing tackle employed. Certain tackle, such as fishing nets, allow for vastly higher return rates and are not comparable to standard hook-and-line tackle (Appeldoorn 1996).[3] Finally, we selected biophysical areas of the *inner-lagoon reef, lagoon passage,* and *outer-lagoon reef drop* habitat types to illustrate how fishers move between different sites. These habitat types are the most important and most widely exploited in the area of the lagoon, and the bulk of our foraging data were collected in grounds with these characteristics.

The data on artisanal fishing for this analysis were gathered by means of a regional creel survey. For each fishing trip, we recorded paddling times to fishing grounds, each spot's habitat type, residence time at each site, total fish weight collected, and the names and numbers of organisms harvested, among other variables. Two research methods were employed: focal follows and self-reporting diaries. Focal follow analysis involved keeping time-motion records for fishers and measuring their catches for each patch visited. The diary method consisted of recruiting randomly selected subjects to keep diaries of their fishing activities. These data were used to explore the effects of village and habitat type on mean net return rates[4] and fishing event duration (e.g., see Aswani 1998*a*, 1998*b* for details).[5]

The next step was to use GIS to link our cartographic spatial data set of indigenously defined resource patches (collected with GPS receivers) with our non-spatial attribute data (foraging data set). To link the data sets in the GIS, at least one field (column) of the non-spatially explicit data table must match a field in the spatially explicit data table. In this case, the indigenous name of the fishing ground was the common attribute of both our foraging and cartographic (GPS) data sets. This allowed us to analyze the spatio-temporal relationships between particular marine habitats and the patches within them, on the one hand, and changes in their relative productivity and associated temporal increases or decreases in foraging effort by members of various regional hamlets to exploit these resources, on the other.

Finally, to provide visualization of the spatio-temporal characteristics of fishing effort we used the querying and display capabilities of GIS. We ran a query with the GIS that extracted the fishing events associated with each of the three locally recognized tidal seasons in the Roviana Lagoon: (1) *masa rane-odu bongi,* or a day low-/night high-tidal season (from May to September); (2) *odu rane-masa bongi,* or day high-/night low-tidal season (from late September to the end of January); and (3) *vekoa kolo,* which is an intermediate tidal season (from February to April).[6] We used GIS to aggregate the mean rate of return measurements and factored the proportional time allocation for each fishing ground of each habitat type for each season. We then displayed and printed these six maps in juxtaposition to enhance visual interpretation and pattern description. To better interpret the data, we

Figure 6. Indigenous Map of the Baraulu MPA
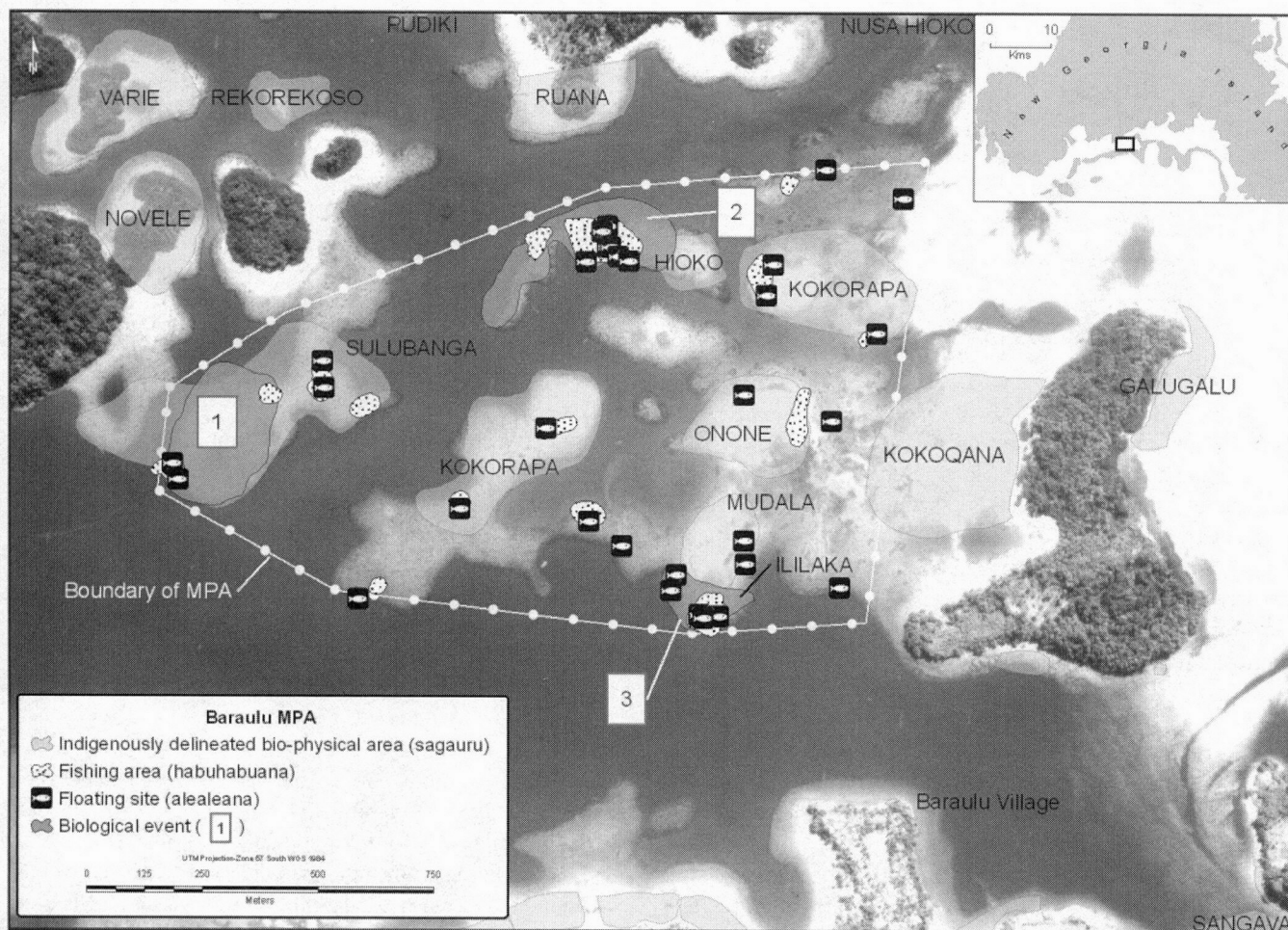
The numbered areas are ecologically important events/characteristics.

Areas 1 and 2: nursery/burrowing site for *topa* (bumphead parrotfish, *Bolbometopon muricatum*). Large *huquru* (*Porites cylindrica*) coral formations occur here.

Area 3: Aggregation site for *heheoku* (paddletail snapper, *Lutjanus gibbus*). Also, large *patu pede* (*Acropora* spp.) coral formations occur here. All areas were mapped with GPS receivers. Note that for display purposes, the *sagauru* layer was placed underneath the *alealeana* and *habuhabuana* layers.

present results for Baraulu and Nusa Hope villages in Eastern Roviana rather than for the entire region.

Results

Spatial Display of Indigenous Ecological Knowledge

Roviana people partition the ocean into named sites that represent biophysical resource extraction areas, features that allow people to, or obstruct them from, navigating, and cultural and historical markers that define the seascapes (*sagauru* used as a generic for "reef"). Next, fishers identified a number of fishing grounds (*habuhabuana*) that are nested within or border on the larger indigenously named and demarcated sites. Fishing grounds, in turn, are composed of one or more areas or floating spots (*alealeana*) in which people actually fish (e.g., a reef outcrop). Finally, underlying these areas are one or more of the locally recognized benthic habitats (and associated biological events) that exist in the lagoons. Visualization of indigenously demarcated areas and associated habitats (illustrated as layers in the GIS) (Fig. 5) afforded a better understanding of the Roviana people's spatial cognition of the sea. Prior to the MPA designation, local people had divided and, with our assistance, geo-referenced spatially the earmarked areas into seven main biophysical areas: *Sulubanga*, *Kokorapa* 1 and 2, *Hioko*, *Onone*, *Mudala*, *Ililaka*, and *Kokoqana* for Baraulu (Fig. 6), and *Sagauru Nusa Hope*,

Figure 7. Indigenous Map of the Nusa Hope MPA
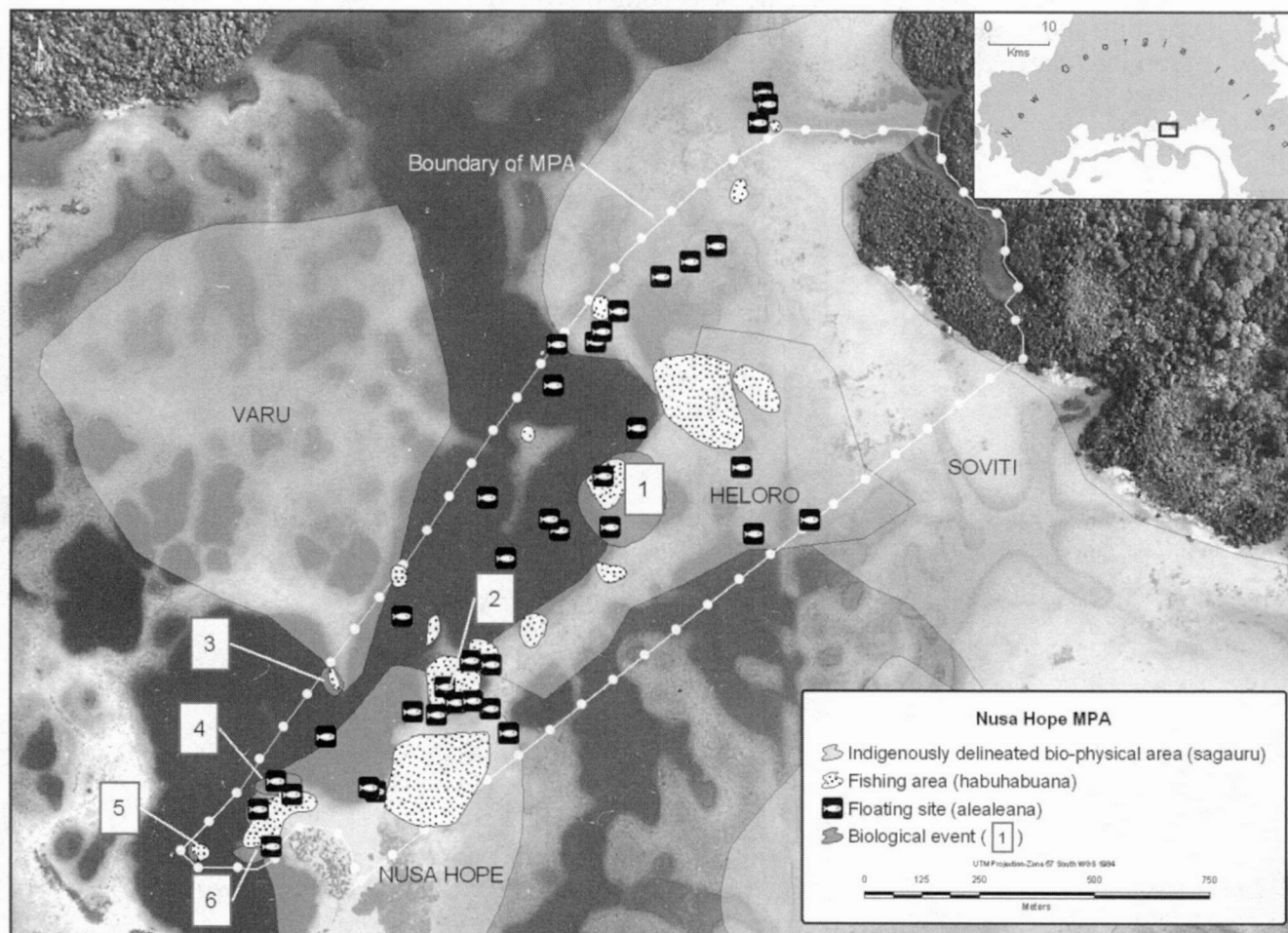
The numbered areas are ecologically important biological events/characteristics.

Area 1: spawning aggregation site for *heheoku* (paddletail snapper, *Lutjanus gibbus*) and aggregation site for *pehu* (brown/giant sweetlips, *Plectorhinchus gibbosus/obscurum*).

Area 2: nesting area for *makoto lio* (yellowmargin triggerfish, *Pseudobalistes flavimarginatus*) and *makoto noa* (titan triggerfish, *Balistoides viridescens*).

Area 3: spawning aggregation site for *pazara haquma* (squaretail coral trout, *Plectropomus areolatus*).

Area 4: nesting area for *makoto lio* and *makoto noa*.

Area 5: nursery/burrowing site for *topa* (bumphead parrotfish, *Bolbometopon muricatum*).

Area 6: nursery/burrowing site for *topa* and aggregation site for *mihu* (long-nosed emperor, *Lethrinus olivaceous*), *kakaha* (mangrove jack, *Lutjanus argentimaculatus*) and *ramusi* (orange-striped emperor, *Lethrinus obsoletus*). All areas were mapped with GPS receivers. Note that for display purposes, the *sagauru* layer was placed underneath the *alealeana* and *habuhabuana* layers.

Heloro, Varu, and *Soviti* for Nusa Hope (Fig. 7). Nested within, Baraulu fishers divided the MPA area into 17 fishing areas (*habuhabuana*) and 31 floating spots (*alealeana*), and Nusa Hope fishers identified 18 and 37, respectively, which were located across different geomorphologic zones (reef drops, reef flats, etc.). Local informants then identified the following habitat types underlying these culturally con- structed sites: reef channels (*karovoana*), reef pools (*kopi*), sand banks (*holehole*), shallow reefs (*sagauru masa*), mid-depth reefs (*sagauru lamana*), seagrass beds (*kulikuliana*), and mangroves (*petupetuana*). Table 1 summarizes how informants distinguished the composite benthic substrates of each habitat (found in the MPA designated areas), which closely resemble the abiotic and biotic group codes detailed

Table 1. Indigenous Classification of Habitats and Associated Benthic Substrates Found in the MPAs [abbreviated] (English and/or Latin binomial counterparts in parenthesis), which Correspond with the Abiotic and Biotic Group Codes Detailed in the Reef Check Survey Manual (Hodgson et al. 2003) and the AIMS Manual for Underwater Research (English et al. 1997).

Indigenous Habitat	Dominant Abiotic Substrates	Dominant Biotic Cover
Petupetuana (mangroves [aquatic zone])	*Kosiri* (silt/clay) *Nelaka* (silt/sand) *Patu horahoraka* (dead coral/stones)	*Kuli* (*Enhalus acoroides* sea grass) *Patu voa* (*Porites* or massive corals)
Kulikuliana (seagrass beds)	*Onone* (sand) *Nelaka* (silt/sand) *Patu horahoraka* (dead coral/stones)	*Kuli* (*Enhalus acoroides* sea grass) *Kuli ngongoto* (various Cymodoceaceae and Hydrocharitaceae sea grasses) *Tatalo, Kakoto, Omomo,* and *Garagara* (*Halimeda* spp. and other macroalgae)
Sagauru Masa (shallow inner-lagoon reef)	*Onone* (sand) *Zalekoro* (rubble) *Patu horahoraka* (dead coral/stones)	*Patu voa* (*Porites* or massive corals) *Patu pede* (*Acropora* spp. or submassive and branching corals) *Huquru* (*Porites cylindrica* or branching corals) *Nene siki* (digitate *Acropora* and other *Seriatopora* branching corals) *Binu* (various hard corals) *Toropae kiso* (*Fungia* spp. or mushroom corals) *Ime* (*Caulerpa* spp. or macroalgae) *Tatalo, Kakoto, Omomo,* and *Garagara* (*Halimeda* spp. and other macroalgae) *Laza keana* (various coralline algae) *Lumulumutu* (various turf algae) *Puha* (generic for sponges)
Sagauru Lamana (mid-depth inner lagoon reef)	*Onone* (sand) *Nelaka* (silt/sand) *Zalekoro* (rubble) *Patu horahoraka* (dead coral/stones)	*Huquru* (*Porites cylindrica* or branching corals) *Patu voa* (*Porites* or massive corals) *Binu* (various hard corals) *Toropae kiso* (*Fungia* spp. or mushroom corals) *Laza keana* (various coralline algae) *Puha* (generic for sponges)
Bolebole (sand bank)	*Onone* (sand) *Zalekoro* (rubble)	*Kuli ngongoto* [sparse cover] (Cymodoceaceae and Hydrocharitaceae sea grasses) *Tatalo, Kakoto, Omomo,* and *Garagara* (*Halimeda* spp. and other macroalgae) *Ime* (*Caulerpa* spp. or macroalgae)
Kopi (lagoon pool)	*Nelaka* (silt/sand) *Onone* (sand) *Zalekoro* (rubble)	Corals may occur on the walls of the pool, but these are generally composed of abiotic substrates.
Karovoana (reef channel)	*Zalekoro* (rubble) *Onone* (sand) *Nelaka* (silt/sand)	Corals may occur on the walls of the channel, but these are generally composed of abiotic substrates.

in the Reef Check Survey Manual (Hodgson et al. 2003) and the AIMS Manual for Underwater Research (English et al. 1997).

Presently, we are conducting an intensive study with local informants to spatially delineate the location and percentage of different abiotic and biotic substrates within non-surveyed MPAs (i.e., reserves established by villages) and potential MPA sites (Aswani and Lauer n.d.). In this paper, however, without complete data on substrate type percentages, we are limited in the analysis to data we have

collected on ecologically important biological events and characteristics, which local informants helped to locate and identify (the exact positions were recorded with GPS receivers). These included alleged spawning aggregation sites for paddletail snapper (*Lutjanus gibbus* [*heheoku*]) and burrowing/nursery sites for bumphead parrotfish (*Bolbometopon muricatum* [*topa*]) in the Baraulu area (Fig. 6), and spawning aggregation sites for various Serranid species (e.g., *Plectropomus areolatus*), burrowing sites for bumphead parrotfish, and nesting areas for two species of triggerfish (*Pseudobalistes flavimarginatus* and *Balistoides viridescens*) among others in the Nusa Hope area (Fig. 7). In addition, we compiled extensive inventories of all organisms at each geo-referenced location, including common fish sighted and/or caught in the area and data on other benthic organisms (Tables 2 and 3). Using GIS, we linked these tables to the geo-referenced fishing ground data.

Spatial Display of Fishing Effort

To analyze and display the spatial characteristics of artisanal fishing, we examined the spatio-temporal relationships between (1) particular marine habitats and changes in their relative productivity (e.g., temporal biological/environmental events that purportedly increased fishing yields), and (2) associated temporal increases in foraging effort by members of various regional hamlets to exploit these resources. The expectation was that fishermen would increase their seasonal overall time allocation (total hours of fishing) to the highest-yielding habitat type (i.e., set of fishing grounds within that habitat type) and decrease overall time allocated to the lowest-yielding habitat or set of grounds.

More overall effort was directed to the habitats with the highest yields for two of the three tidal seasons, while habitats with lower returns were not visited as often. These patterns, however, varied across the two villages. In Baraulu, overall time allocation to habitats increased when habitat seasonal productivity increased and was higher than that for other habitats during the day high (*odu rane*) and intermediate (*vekoa kolo*) tidal seasons (note the patches of darker grayscale color in the lower two pictures of the left and right columns of Figure 8). At Nusa Hope, in contrast, this pattern was apparent during the day low (*masa rane*) and day high (*odu rane*) tidal seasons (note the patches of darker grayscale color in the upper two maps of the left and right columns of Figure 9).

Despite divergences in the total time allocated to productive habitats seasonally, there were periodic parallels in patterns of site visits (and concomitant in-patch time use) between the villages. For instance, the number of visited inner-lagoon sites changed significantly across the seasons (chi^2 [df = 2, N = 89] = 8.2, p < 0.02). More inner- than outer-lagoon reefs were visited by both Baraulu (sign test, p < 0.02) and Nusa Hope (sign test, p < 0.00001). The villages were similar (chi^2 [df = 2, N = 89] = 0.04, p = 0.84, n.s.) in their seasonal patterns, with more inner-lagoon shallow reefs

(top section of Figs. 8 and 9) visited during the day low-tide season, fewer during the day high-tidal season, and fewest during the intermediate tidal season. In contrast, the number of visited outer-lagoon reef grounds remained constant throughout the three tidal seasons for both villages (chi^2 [df = 2, N = 33] = 0.06, p = 0.81, n.s.).

In the case of the inner-lagoon reefs, it is conceivable that during the day low-tide season a shifting strategy permitted fishermen to avoid a dramatic drop in their mean energy intake during fishing. That is, the number of patches increased (and the "per bout time" decreased) because fishermen could find numerous alternative productive patches within close range. With a shift in seasons and changes in average return rates, fishermen began to pay more attention to other habitats and visit fewer inner-lagoon reefs (or to spend more time in fewer patches in the Nusa Hope case). In contrast, it is plausible that in the outer-lagoon reef drops case fewer patches were visited because travel times to these grounds were higher than to other habitats. Once fishermen made it to these grounds (i.e., after the fisher had paid the traveling costs of paddling out) it paid to stay in the patch (and thus the "per bout time" increased) even under conditions of declining yields. Switching of behavior, as in these cases, has been predicted by time-allocation models such as the marginal value theorem (MVT).

The visual representation of Table 4 in figures 8 and 9 (as disaggregated data) illustrates major themes in spatial patterning. In general, there were clear differences in the percentage of time allocated to different habitats between Baraulu and Nusa Hope across seasons. Throughout the year, the lagoon passage habitat was more intensively exploited at Baraulu, whereas the inner-lagoon reefs were visited more often in Nusa Hope. During the day low-tide season, fishers in Baraulu frequented the passage most intensively and allocated equal proportions of overall time to the inner- and outer-lagoon reefs (top section of Fig. 8). Nusa Hope fishers frequented the inner-lagoon reefs and the passages (top section of Fig. 9). However, with the advent of the day high-tide season (*odu rane*) (mid section of Figs. 8 and 9), Baraulu fishers intensified their activities in the passage and outer reef drop habitats, whereas Nusa Hope fishers continued to focus their effort on the inner-lagoon reefs and passage. Finally, during the intermediate tidal season (*vekoa kolo*), Baraulu fishers focused almost entirely on the passage, while Nusa Hope fishers continued to exploit inner-lagoon reefs and shifted some attention away from the passage onto the outer-lagoon reef drops (bottom section of Figs. 8 and 9). Overall, then, Nusa Hope inhabitants did not exploit the outer reef and lagoon passage as intensively as did the Baraulu fishers. They did not need to, as their bordering shallow reefs are among the richest in the Roviana Lagoon and productivity is high year round in these grounds.

Our study also revealed some subtleties in intra-habitat spatial patterning. In Baraulu, during the day high-tidal season (mid-section in the left column of Fig. 8) the net return rates for almost all of the outer reef drops increased when compared with the day low-tidal season (top section in the left column of

Table 2. General Characteristics of Indigenously Delineated Biophysical Areas within the Baraulu Village Marine Protected Area (based on local knowledge)

Fishing Ground Name	General Characteristics	Common Prey Species (fish)	Common Prey Species (others)	Significant Biological Events
Sulubanga	Shallow and mid-depth reef with some *Porites* coral heads, extensive *Porites cylindrica* colonies, some coral rubble, and silt mixed with various Cymodoceaceae and Hydrocharitaceae sea grasses	*Bolbometopon muricatum* *Lethrinus elongatus* *Lutjanus gibbus/L. adetii* *Lethrinus harak* *Lethrinus obsoletus* *Lethrinus hypselopterus* *Pseudobalistes flavimarginatus* *Balistoides viridescens* *Siganus* spp. Various Serranids Various Carangids	*Anadara antiquata* *Gafrarium tumidum* *Chama* spp. *Thalamita* spp. Various Holothurians	Nursery and burrowing area for bumphead parrotfish (*Bolbometopon muricatum*) of various size classes
Sagauru Kokorapa I	Shallow reef with numerous *Porites* coral heads, sandy substrate, and some Cymodoceaceae and Hydrocharitaceae sea grasses	*Lutjanus gibbus/L. adetii* *Lethrinus harak* *Lethrinus obsoletus* *Lutjanus fulvus* *Epinephelus ongus* *Lethrinus hypselopterus* *Pseudobalistes flavimarginatus* Balistoides viridescens Choerodon anchorago	*Anadara antiquata* *B. semiorbiculata* *Gafrarium tumidum* *Thalamita* spp. *Caulerpa* spp. Various Holothurians	Spawning area for paddletail snappers (*Lutjanus gibbus*)
Sagauru Kokorapa II	Shallow sand bank with extensive beds of Cymodoceaceae and Hydrocharitaceae sea grasses	*Lethrinus harak* *Lethrinus obsoletus* *Lethrinus hypselopterus* *Lutjanus gibbus/L. adetii* *Sphyraena barracuda* *Pseudobalistes flavimarginatus* *Balistoides viridescens* *Choerodon anchorago* *Scolopsis monogramma* *Pentapodus* spp. *Valamugil seheli* Various Carangids	*B. semiorbiculata* *Anadara antiquata* *Gafrarium tumidum* *Caulerpa* spp. Various Holothurians	None
Hioko	Mid-depth reef with extensive *Porites cylindrica coral* colonies and coral rubble	*Bolbometopon muricatum* *Lutjanus gibbus/L. adetii* *Lutjanus fulvus* *Lethrinus obsoletus* *Lethrinus hypselopterus* *Pseudobalistes flavimarginatus* *Balistoides viridescens* *Sphyraena* spp. *Monotaxis grandoculi*	*B. semiorbiculata* *Thalamita* spp. *Caulerpa* spp. Various Holothurians	Nursery and burrowing area for bumphead parrotfish (*Bolbometopon muricatum*) of various size classes
Sagauru Onone	Shallow sand bank with with coral rubble, *Porites* coral heads, and some Cymodoceaceae and Hydrocharitaceae sea grasses.	*Lethrinus harak* *Lethrinus obsoletus* *Lethrinus hypselopterus* *Lethrinus olivaceus* *Sphyraena barracuda* *Pseudobalistes flavimarginatus* *Balistoides viridescens* *Choerodon anchorago*	*Anadara antiquata* *Gafrarium tumidum* *B. semiorbiculata* *Antigona* spp. *Caulerpa* spp. Various Holothurians	None

Table 2. (con'd.)

Fishing Ground Name	General Characteristics	Common Prey Species (fish)	Common Prey Species (others)	Significant Biological Events
Sagauru Kokoqana	Shallow reef with *Porites* coral heads, sandy substrate mixed with silt and mostly *Cymodoceaceae* and *Hydrocharitaceae* sea grasses	*Lutjanus gibbus/L. adetii* *Lethrinus harak* *Lethrinus obsoletus* *Lethrinus hypselopterus* *Sphyraena barracuda* *Pseudobalistes flavimarginatus* *Balistoides viridescens* *Choerodon anchorago* *Scolopsis monogramma* *Pentapodus* spp. *Valamugil seheli* Various Carangids	*Anadara antiquata* *Antigona* spp. *B. semiorbiculata* *Gafrarium tumidum* *Caulerpa* spp. *Hyotissa hyotis* *Spondylus* spp. *Pinctada magaritifera* *Chama* spp. Various Holothurians	Schools of herring (*Herklotsichthys quadrimaculatus*) commonly seen during the full moon
Sagauru Mudala	Mid-depth reef with numerous *Porites* coral heads, some *Acropora* and *Porites cylindrica* coral colonies, mostly *Cymodoceaceae* and *Hydrocharitaceae* sea grasses, and silt/sand substrates	*Lutjanus gibbus/L. adetii* *Lutjanus argentimaculatus* *Lutjanus carponotatus* *Lutjanus fulvus* *Lethrinus harak* *Lethrinus obsoletus* *Lethrinus olivaceus* *Pseudobalistes flavimarginatus* *Balistoides viridescens* Various Carangids Various Serranids	*Antigona* spp. *Hyotissa hyotis* *Spondylus* spp. *Pinctada magaritifera* *Acrosterigma* spp. *Chama* spp. *Pinna* spp. *B. semiorbiculata* *Thalamita* spp. *Panulirus versicolor* Various Holothurians	Turtle and dugong often seen here. Groups of surgeonfish (*Acanthurus* spp.) seen foraging regularly
Sagauru Ililaka	Mid-depth reef with numerous *Porites* coral heads and some *Acropora* and *Porites cylindrica* coral colonies. Slopes into lagoon channel	*Lutjanus gibbus/L. adetii* *Lutjanus argentimaculatus* *Lutjanus carponotatus* *Lutjanus fulvus* *Lethrinus harak* *Lethrinus obsoletus* *Lethrinus olivaceus* *Pseudobalistes flavimarginatus* *Balistoides viridescens* Various Carangids Various Serranids	*Antigona* spp. *Hyotissa hyotis* *Spondylus* spp. *Pinctada magaritifera* *Acrosterigma* spp. *Chama* spp. *Pinna* spp. *B. semiorbiculata* *Thalamita* spp. *Panulirus versicolor* Various Holothurians	Spawning area for paddletail snappers (*Lutjanus gibbus*)

Fig. 8). But in terms of total time allocation, even though there was an overall increase in the total time spent at the outer-reef drop-off habitat, as would be predicted by the patch choice model, much of it was concentrated in one single fishing ground to the southeast of the lagoon passage (see the middle map in the right column of Fig. 8). Visual representation made these sorts of details more apparent and hence gave us a better understanding of intra-habitat variability and human responses to and strategies for dealing with this variability. In fact, if the scale of the system increases from several dozen fishing grounds, as in these examples, to several hundreds or thousands (as we are undertaking currently), the displaying capabilities of GIS to make sense of spatial patterns become even more powerful. Through visualization, we can now see deeper and farther into larger data sets, allowing questions to be asked that were not apparent before.

Discussion

The approach presented in this paper can help in the selection of sites for establishing marine protected areas. The geo-spatial referencing of indigenous ecological knowledge aids in the spatial identification of habitat diversity (or lack thereof), in the bio-geographical representation (when habitat delineation is done on a large scale), and in the identification of vulnerable habitats and life stages (conceptualized as the association between habitat structure and species size and distribution), sites of rare and or endangered species, and locations of exploited species. This knowledge can be used to select sites according to their general habitat quality and representation and to concomitantly incorporate the ecological processes that support biodiversity, including the presence of exploitable species, vulnerable life stages,

Figure 8. Spatio-temporal Characteristics of Artisanal Fishing Around Baraulu Village (Seasonal mean net rate of return for fishing grounds of different habitat types are shown on the left side of the figure, and the percentage of total seasonal foraging time in those same fishing grounds is shown on the right side.)
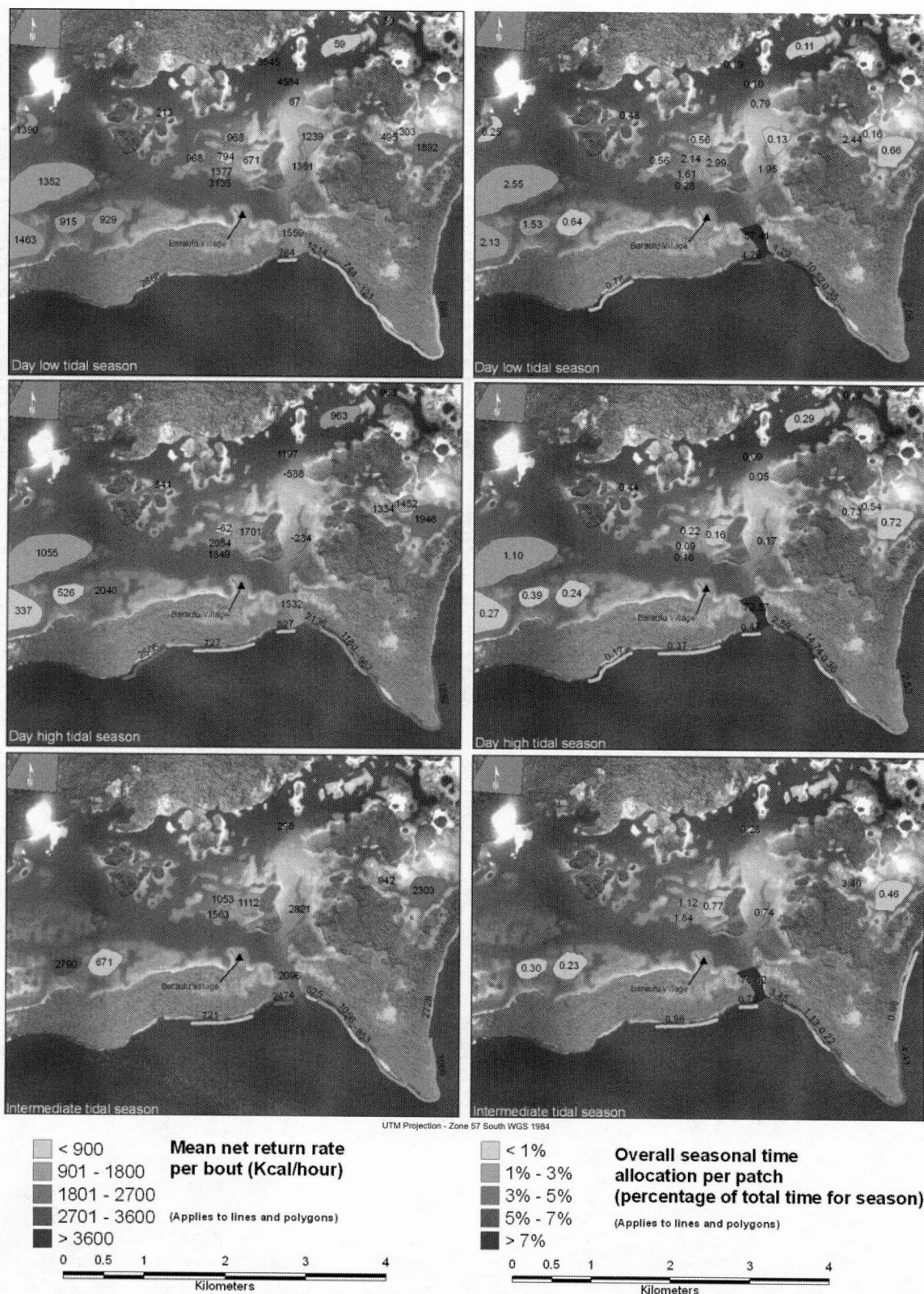
Table 3. General characteristics of indigenously delineated biophysical areas within the Nusa Hope Village Marine Protected Area (based on local knowledge)

Fishing Ground Name	General Habitat Characteristics	Common Prey Species (fish)	Common Prey Species (others)	Significant Biological Events
Sagauru Nusa Hope	Shallow and mid-depth reef with some *Porites* coral heads and dead and live *Acropora, Millepora, Faviidae, Agariciidae,* and *Pocillopora* coral colonies. Also, some coral rubble and silt mixed with Cymodoceaceae and Hydrocharitaceae sea grasses. The reef slopes into lagoon channel	*Bolbometopon muricatum* *Cheilinus undulatus* *Pseudobalistes flavimarginatus* *Balistoides viridescens* *Lethrinus hypselopterus* *Lethrinus erythracanthus* *Lethrinus olivaceous* *Lutjanus gibbus/L. adetii* *Monotaxis grandoculis* Various Serranids Various Carangids	*B. semiorbiculata* *Lopha cristagalli* *Thalamita* spp. *Caulerpa* spp. *Spondylus* spp. Various Holothurians	Important nesting area for triggerfishes (*Pseudobalistes flavimarginatus* and *Balistoides viridescens*). Also, bumphead parrotfish (*Bolbometopon muricatum*) burrow here at night
Sagauru Varu	Shallow reef with *Porites* coral heads, sandy substrate mixed with coral rubble. Slopes into lagoon channel with mixed coral species	Lethrinus obsoletus *Lethrinus harak* *Lethrinus obsoletus* *Lutjanus gibbus/L. adetii* *Lutjanus rivulatus* *Pseudobalistes flavimarginatus* *Balistoides viridescens* *Monotaxis grandoculis* Various Serranids Various Carangids	*B. semiorbiculata* *Pinctada magaritifera* *Lopha cristagalli* *Pinna* spp. Various Holothurians	Spawning aggregation of squaretail coral grouper (*Plectropomus areolatus*) occurs here. Also, possibly *Epinephelus fuscoguttatus* and *E. polyphekadion**
Sagauru Heloro	Shallow and mid-depth reef with some *Porites* coral heads and dead and live *Acropora Millepora, Faviidae, Agariciidae,* and *Pocillopora* coral colonies. Also, coral rubble and silt mixed with Cymodoceaceae and Hydrocharitaceae sea grasses. The reef slopes into lagoon channel	*Pseudobalistes flavimarginatus* *Balistoides viridescens* *Lethrinus obsoletus* *Lethrinus hypselopterus* *Lethrinus olivaceous* *Lutjanus gibbus/L. adetii* *Lutjanus rivulatus* *Lutjanus argentimaculatus* Various Serranids Various Carangids	*B. semiorbiculata* *Lopha cristagalli* *Anadara antiquata* *Gafrarium tumidum* *Thalamita* spp. *Caulerpa* spp *Spondylus* spp *Pinctada magaritifera* Various Holothurians	Important nesting area for triggerfishes (*Pseudobalistes flavimarginatus* and *Balistoides viridescens*)
Soviti	Shallow sand bank with extensive beds of Cymodoceaceae and Hydrocharitaceae sea grasses. Dead and live *Porites* corals. The sand bank slopes into silt drop-off. The area is also bordered by mangroves	*Lutjanus gibbus/L. adetii* *Lethrinus harak* *Lethrinus obsoletus* *Lethrinus hypselopterus* *Sphyraena barracuda* *Pseudobalistes flavimarginatus* *Balistoides viridescens* *Choerodon anchorago* Scolopsis monogramma Pentapodus spp. *Valamugil seheli* Various Carangids	*B. semiorbiculata* *Anadara antiquata* *Anadara granosa* *Gafrarium tumidum* *Nassarius camelus* *Saccostrea cucullata* *Caulerpa* spp. *Scylla serrata* Various Holothurians	None

* Richard Hamilton personal communication (also based on IEK).

and inter-connectivity among habitats (Roberts et al. 2003). Similarly, the geo-referencing of fishing behavior permits the visualization of spatio-temporal human resource exploitation patterns (seasonal changes in fishing gear), human responses to variability in inter- and intra-habitat relative productivity (as determined by catch rates) and the influence of this variability on fishing strategies, and human threats to particular marine habitats. This information can help in the design of permanent and seasonal closures modeled in accordance with human seasonal foraging patterns.

At Baraulu, for instance, the passage was the most heavily used zone year round and the area that, on average, furnished the highest mean rate of return per hour of foraging (Fig. 8). Establishing an MPA in this area would have met with community resistance, given that a closure would interfere with local subsistence activities and deprive people of their primary source of protein.[8] The selected MPA site was only used intensively during the low-tide season and, therefore, was less vital for subsistence than the passage, which made its closure more acceptable locally. For the Nusa Hope case, however, the GIS visual representation illustrated that the inner-lagoon reef habitat was of vital subsistence importance. Given that there are multiple productive nearby sites and that the Heloro reef area is not exploited intensively (in Fig. 9, note that it was not used by the fishers sampled in 1994-95), closing the area was more acceptable to local people, nonetheless. GIS visual representation made spatio-temporal differences in human fishing patterns more apparent than would have been the case if only interviews or participation in people's fishing activities had been relied upon. This made the management plan less disruptive to local subsistence patterns, more participatory (via participatory mapping and joint interpretation of GIS results), and thus overall more acceptable. Moreover, it generated maps of local foraging patterns that could be shown locally to aid in the MPA designation process. Finally, the analysis also made differences in foraging strategies between villages more apparent, thus alerting us to the pitfalls of using localized fishing strategies to infer more general lagoon patterns. It is worth noting that the information gathered through the intersection of spatial tools, anthropological fieldwork, and social and natural science is often cited as a fundamental criterion for selecting marine reserve sites and establishing MPA networks (Friedlander et al. 2003; Halpern 2003; Roberts and Hawkins 2000; Roberts et al. 2003).

We do not offer this mapping of indigenous ecological knowledge and foraging patterns via participatory GIS as an absolute substitute for marine science habitat mapping research for designing MPAs. We also recognize that indigenous ecological knowledge regarding biological processes (e.g., spawning aggregations) is not always accurate and should, in some instances, be validated scientifically. We do, nonetheless, suggest that in the absence of complete marine science information, as is the case in many areas of the Western Pacific (Johannes 1998), our methods can be used locally to design MPAs (the ideal, of course, is to integrate both forms of knowledge). Scholars are increasingly calling

Table 4. Total Percentage of Time Allocated to Different Habitats between Baraulu and Nusa Hope Fishermen Across Tidal Seasons in One Year (1994–95)

Tidal Seasons	Baraulu Village	Nusa Hope Village
Day Low-tide		
Inner Reefs	21.7	55.3
Outer Reefs	20.2	7.4
Passage	57.4	36.4
Day High-tide		
Inner Reefs	5.7	58.6
Outer Reefs	21.5	2.7
Passage	72.6	38.6
Intermediate		
Inner Reefs	9.1	51.5
Outer Reefs	12.1	24.3
Passage	78.8	23.5

for the inclusion of indigenous ecological knowledge and local participation in the design of conservation programs (Poizat and Baran 1997; Silvano and Begossi 2005). However, there are few case studies that provide hands-on examples of how indigenous ecological knowledge (Anuchiracheeva et al. 2003) and socio-ecological behavior can be made operational in a resource management context via the intersection of various natural and social research approaches and geomatics.

The Baraulu and Nusa Hope MPAs were established in 2002 in order to: (1) preserve representative lagoon shallow-reef habitats; (2) provide a safe heaven for bumphead parrotfish as well as other endangered species (e.g., turtles that graze in the MPA grassbeds); (3) safeguard bumphead parrotfish nursery areas; (4) protect the spawning grounds of various species; and (5) allow for the ecological restoration of habitats within the MPAs. Indeed, at some level, indigenous ecological knowledge is more coarse and anecdotal than scientific evidence. However, it is worth noting that a scientific survey to independently assess habitat structure in the Baraulu MPA showed that indigenous photo aerial interpretation of benthos match results from conventional marine science research (quadrat field-dive surveys) closely. The accuracy rate for indigenous aerial photo interpretation ranged between 70 and 80 percent for a moderately detailed classification of the benthos, which included 9 locally defined abiotic and biotic benthic classes. Such correspondence is promising, given that it corroborates an intuitive prediction that indigenous ecological knowledge as a form of inductive science is not ontologically incongruent with Western scientific knowledge. From the standpoint of Western experts, it is an apt reservoir of knowledge (for the local people it is culturally embedded

Figure 9. Spatio-temporal Characteristics of Artisanal Fishing around Nusa Hope Village (Seasonal mean net rate of return for fishing grounds of different habitat types are shown on the left side of the figure, and the percentage of total seasonal foraging time in those same fishing grounds is shown on the right side.)
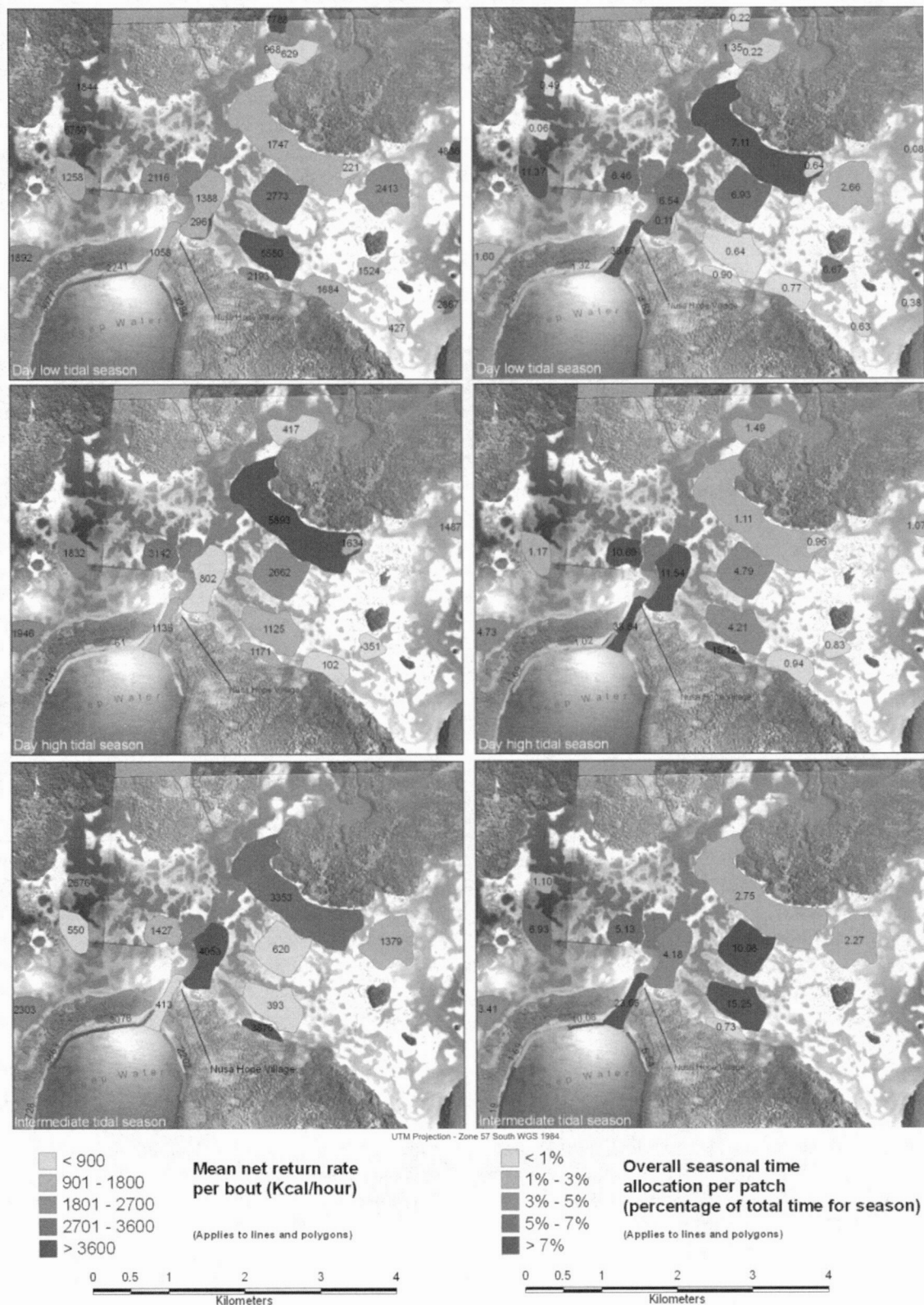
and appropriate knowledge anyway) that can complement efforts to delineate and design MPAs and other conservation measures. In our case, limited scientific baseline data were used to design the Baraulu and Nusa Hope MPAs, but the *post facto* scientific monitoring results have shown the value of a preventive management strategy that relies heavily on local knowledge. This experience should be useful to conservation biologists and fisheries managers who are working in data-less contexts.

Indeed, we lack data on the life history and larval and adult dispersal characteristics for most species, which would be needed to make fully scientifically informed decisions when designing MPAs (Botsford et al. 2003). Nonetheless, we believe that our integrative natural and social science approach for selecting MPA sites and placing them in a network system can yield positive biological and social results. Biologically, we expect that the reserve network will provide protection for representative habitats and for exploited marine organisms while enhancing artisanal fisheries productivity. A network of small, inner-lagoon reserves is critical for protecting vulnerable life-history stages of many heavily exploited coral reef fishes. The larvae of these fish predominantly settle out of the plankton into shallow water biotopes of high structural complexity such as mangroves and seagrass beds (Nagelkerken et al. 2000). The importance of the nursery function of the lagoon for coral reef fish species in this region can be inferred from the high densities of juveniles in the inner lagoon in contrast to their complete absence in outer-lagoon coral reef areas (Aswani and Hamilton 2004*b*; Hamilton 2004). There is an increasing amount of theoretical modeling data suggesting that networks of reserves create buffers against the vagaries of environmental variability and provide significantly greater protection for marine communities than single reserves (Hastings and Botsford 2003; Roberts et al. 2003).

The resulting biological outcomes of the MPAs[9] are a tangible means of socially demonstrating the significance of resource management and environmental stewardship. Fundamentally, by witnessing positive environmental change (whether real or perceived), the Roviana people are encouraged to adopt more sustainable harvesting practices, which, in turn, are increasing levels of food security and environmental and human health, and reducing resource conflicts across the region.[10] In summary, our stakeholder-driven approach is: (1) based on precautionary and adaptive management principles (we are currently evaluating various biological and social outcomes of our strategy in order to fine-tune our MPA network design) (Johannes 1998; Parma et al. 1998); (2) highly dependent upon local socio-economic, political, cultural, and ecological processes; and (3) a countervailing force against human mismanagement of the marine environment.

Finally, the ability of GIS to translate information into a format that is accessible and interpretable is important for researchers, particularly when working in areas of the developing world where various stakeholders, including government authorities, conservation groups, indigenous rights advocates, scientists, and local people, are all participating in management decisions. We endorse the use of GIS for conservation work, although we accept some criticisms of the use of these technologies (Craig et al. 2002; Harris and Weiner 1998; Obermeyer 1998; Pickles 1995), particularly critiques that argue that the increased use of GIS in projects can exacerbate the differences in power between outsiders and locals and further marginalize the latter from the decision-making process. Through "public participation GIS" (Poole 1995; Robbins 2003), however, such asymmetries can be ameliorated. Social and natural scientists can employ participatory mapping techniques (Herlihy and Knapp 2003) and GIS technologies to help indigenous peoples by co-producing maps that help present indigenous peoples' claims over their land and sea estates, to enable resource management through the incorporation of local cultural knowledge and ecological values (Flanagan and Laituri 2004), to employ participatory mapping in local environmental and resource education (Herlihy 2003), and to survey biodiversity and design conservation programs (Poole 1995). Researchers can create maps of local habitats and conservation areas that represent indigenously cognized and delineated natural and social seascapes.

In this case, the MPA boundaries were contentious issues, and we wanted to maintain the highest level of accuracy when the communities ultimately decided upon where the boundaries would be drawn. Initially, with the help of members of each of the respective communities, we mapped the boundaries of the MPAs around the previously surveyed habitats (using the methods outlined herein). Then, in community meetings, the respective communities reviewed these printed maps to ensure that they agreed upon the boundaries. With the communities' approvals, the maps of each MPA were then posted in public places (airport, churches, meeting halls, etc.) in the Roviana and Vonavona Lagoons so that the entire lagoon community was aware of the establishment of the protected areas. As visual aids, these hard-copy maps were invaluable because local people could easily recognize the areas under protection and the habitats and species that were targeted for management and conservation. To deepen and broaden the participation of local communities in the management of their marine resources and in locally contextualizing sea tenure rights, we are currently training our local coordinators in the use of GIS and supplying computers and GIS software to various villages and local schools.

The overall effectiveness of community-based management and participatory schemes such as those outlined above has been recently questioned (Barrett et al. 2001; Kellert et al. 2000). Engaging in this debate is beyond the scope of this paper, but it is worth noting that failure of community-based management projects often originates from the ineffective implementation of co-management plans (at various levels) between local communities and outside government and non-government organizations. That is, outside agencies often unsatisfactorily integrate local stakeholder groups (who are often at odds) into the designation, implementation, governance, management, and monitoring processes related to

community-based protected areas. As pointed out by Berkes (2004: 629), in order for community-based management to work, external agencies need to share with local communities truthfully and transparently (or the various competing groups of stakeholders) "management power and responsibility—as opposed to token consultation and passive participation" and they must create a context "that encourages learning and stewardship and builds mutual trust." The participatory GIS example illustrated in this paper shows channels by which such participatory engagements can begin to be built. We are confident of the accuracy of this statement because our 2005 Social Impact Assessment (SIA) shows local support rates for the MPAs of between 70% and 90% in all regional hamlets.

Conclusion

The ability of a GIS to store, retrieve, analyze, and display spatial characteristics of complex systems makes it an excellent spatial analytical tool for deepening our knowledge of the socio-ecological dimensions patterning a system—an understanding that affords better managerial solutions to complex social and environmental problems. In this paper, we show how GIS can be integrated with a broader human ecological analysis to reveal the spatial and temporal patterning of Roviana fishermen's ecological knowledge and fishing behavior. Through querying and then displaying our data using GIS, we employ spatial analysis tools that allow for visualization and pattern recognition. Displaying data in this way is particularly effective when working with local people in situations where visual aids help to bridge the divide between local indigenous knowledge and scientific knowledge. Indeed, the data used to illustrate these examples was assembled over a period exceeding 10 years. With adequate logistical and research planning, however, these methods can be applied successfully within several months of fieldwork and can be used in most marine or terrestrial contexts in the world. In addition, the recent decline in the cost of computers capable of efficiently running GIS software and the widespread availability of inexpensive GPS equipment and satellite imagery have placed GIS within the reach of most researchers.

In conclusion, integrated analyses seem all the more urgent considering the emphasis over the past decade in the social and natural sciences on the human dimensions of environmental change. GIS holds great potential for applied anthropologists who can give historical and cultural dimensions as much weight as biophysical ones in conservation and resource management initiatives. In our case, mapping the seascape through participatory research has allowed for the management of resources through the use of local ecological knowledge and values within a system that integrates as equivalents indigenous and Western forms of knowledge. Because of the increasing popularity of MPAs as a fisheries management and conservation tool around the world, it is now of fundamental importance to design these by integrating multiple research approaches more comprehensively. It is also essential that we offer the stakeholders who are going to have to accept or reject a marine protected area an equal voice in its design, demarcation, implementation, and monitoring. Only then can we hope to achieve management regimes that are truly participatory and that will sustain biological and social resources over the long term.

Notes

[1] The conservation, development, and education initiatives were offered to the local residents as integral components of a three-pronged approach to rural development rather than trade-offs for their MPAs.

[2] Note that we were mindful of the age of these photographs and careful when identifying cultural and geo-physical features that might have changed since 1984.

[3] Netting and mass-harvesting drive events are very important methods to consider when analyzing local patterns of resource use, and we have independently mapped their occurrence across the lagoon to inform our management decisions. These fishing events, however, were not appropriate for our optimal foraging analysis, as they greatly skewed results by blurring the most common local patterns of resource utilization (i.e., hand-lining).

[4] The *mean net return rate* measure (Smith 1991), which was used to estimate relative abundance, is similar to a catch-per-unit-effort (CPUE) concept. This measurement is equivalent to the energy gained during fishing (the kcal value of the edible catch) minus the labor input (labor costs incurred during foraging, including travel, search, and handling times) divided by the total residence time at a fishing ground. Labor cost is factored by multiplying minutes spent in a certain activity (e.g., paddling a canoe or hand lining) by standardized measures from published sources (indirect calorimetry measurement for various activities adjusted for age, weight, and sex [i.e., basal metabolic rate or BMR]).

[5] Overall, a data set encompassing over 10,000 fishing events and extending for more than 15,000 hours of fishing time for the entire Roviana and Vonavona Lagoons was collected during a 10-year period (1994-2004). Currently, we are importing all of this data into the GIS for a regional spatio-temporal analysis of fishing patterns.

[6] Note that not all informants recognize this time as a specific tidal season and continue to refer to this period as *odu rane*. The term *vekoa kolo* ("staying water") refers to small fluctuations in tidal levels with 24-h persistence of mid- and high tides (or neap tides). The term *vekoa kolo*, nonetheless, is used here to refer to a period when there is a clear change in tidal patterns and associated fishing activities (at least during 1994-1995).

[7] It is possible that these differences result from different habitat structures between sites and from lagoon hydrology, which may be what make the Nusa Hope inner reefs so productive. These differences have to be taken into account when designing MPAs.

[8] Closing the Baraulu passage would not make much biological sense anyway, given that the passage is a transit area for multiple pelagic species. There are other passages in Roviana, however, that are more significant biologically, in that they house a number of spawning aggregations.

[9] Our first monitoring efforts are showing that while fish densities between MPA and non-MPA sites are not significantly different, fish tend to be larger inside the MPAs. Because the reserves are only 2-3 years old, more monitoring will be needed to determine whether or not the MPAs are having a significant biological effect (Ben Halpern

personal communication). Note, however, that three years of monitoring of mud clams and blood cockles in the Baraulu area has shown statistically significant differences in the abundance and size distribution of these bivalves between closed- and open-access sites (see Aswani and Weiant 2004).

[10]Preliminary data analysis of a health and nutrition survey conducted in Roviana in 2005 suggests that the MPAs are not having an adverse effect and that, in some instances, are improving local nutrition (Aswani and Furusawa, unpublished data).

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